least 500 kHz and a processing gain of at least 10 dB, which means that the spread bandwidth must be roughly ten times the information bandwidth, or more. The spectrum-spreading can reduce the interference caused by the Part 15 device if the "spread" Part 15 signal has a bandwidth greater than that of the victim receiver, which will "see" only a fraction of the power from the Part 15 device. For a wideband receiver such as Teletrac's, however, it will not have much impact on the interference potential in many cases. Consider, for example, a system with an information bandwidth of 100 kHz and a spread bandwidth of 1 MHz. Depending on channel alignment, the entire spectrum of the Part 15 transmitter can fall within the receive bandwidth of the Teletrac receiver. Further, several such Part 15 devices can fall within the Teletrac receiver's passband without interfering with each other. Hence, unless it spreads its signal over a very wide band, a Part 15 device using direct sequence modulation poses essentially the same interference threat to the Teletrac system as it would using conventional narrowband modulation.

The frequency hopping requirements in §15.247 require that a device operating in the 902-928 MHz band use a hop sequence consisting of at least 50 randomly-selected frequencies, and transmit on each frequency no longer than 400 milliseconds at a time. This means that on the average, a single frequency hopper will be operating within a given 8 MHz bandwidth roughly 30% of the time. If there are k frequency hoppers operating near a Teletrac receiver, the probability that at least one of them is within a given 8 MHz bandwidth at any given time is $1 - 0.7^k$, assuming their hop sequences are random and mutually independent. Thus, if there are 2 hoppers, the probability that a given 8 MHz band is "clear" is 49%; for 3 hoppers it is 34%, and for 4 hoppers it is 24%. It should also be noted that this problem will not tend to be alleviated to any great extent by interference among the hoppers themselves. First, several hoppers may have good propagation paths to the Teletrac receiver due to its high elevation, but poor paths to each other, if they are near the ground. They therefore may cause no discernible interference to each other. Second, due to the wide bandwidth of the Teletrac receiver, a number hoppers with relatively narrow channel bandwidths (e.g., 100-200 kHz) can operate within the same Teletrac receiver bandwidth simultaneously without causing cochannel interference to each other, even if they are operating in close proximity.

It appears, therefore, that the spread spectrum requirement in §15.247 associated with the allowed 1-watt transmit power will not significantly mitigate the interference threat posed by Part 15 devices to receivers of systems such as Teletrac's. Further, the wider the bandwidth of the AVM receivers, the more severe the problem.

5. CONCLUSIONS

This discussion has focussed on the receiver in a Teletrac base station, the function of which is to estimate the time-of-arrival (TOA) of a signal pulse received from the vehicular transmitter. Of interest is the relationship between the TOA estimation error and the interference sustained by the base receiver. The performance of the Teletrac receiver (as given in Teletrac's Comments [2] was reviewed and compared to the Cramer-Rao bound, which gives a lower limit on the rms TOA estimation error as a function of the RF carrier-tonoise ratio (CNR). In both cases, the rms TOA estimation error varies inversely with the square root of the CNR, and the Teletrac receiver's performance is within about 5-6 dB of the Cramer-Rao bound. However, the inverse-square-root relationship only applies when the CNR is above the receiver's threshold, which for the current version of the Teletrac receiver, appears to be about -25 dB. When the CNR drops below this level, the rms TOA estimation error seems to vary roughly as the inverse-square of the CNR. This threshold effect has not been taken into account in the arguments of bandwidth-versus-capacity tradeoffs made by Teletrac. Taking into account the threshold effect, it appears that the claimed "bandwidth squared" capacity gain is illusory, as explained in section 3. In fact, the maximum capacity of a system will increase only as the square root of the bandwidth, given a maximum allowable rms TOA estimation error. Hence, the argument that more bandwidth is needed to support larger capacities does not appear valid.

Section 4 provided calculations of desired and interfering signal power as seen by a Teletrac receive base station, and it was shown that a Part 15 device with a line-of-sight path to a base station (which may not be unusual, considering that the base stations are typically elevated several hundred feet above the terrain, to maximize coverage) can deliver interference power levels of -30 to -60 dBm into the receiver, which will essentially render the receiver useless. This analysis considered only a single interference source, but as the penetration of Part 15 devices grows, it may not be uncommon for several such devices to fall within the wide Teletrac reverse channel passband simultaneously. Clearly, the wider the Teletrac reverse channel bandwidth, the greater the vulnerability to uncontrolled interference.

Based on the results given here, it is concluded that Part 15 devices in the 902-928 MHz band constitute a serious interference threat to systems such as Teletrac's that depend on reception of relatively weak signals. The question of how often interference incidents will occur is beyond the scope of this paper, because that depends on the penetration achieved by Part 15 devices. However, the increase in that penetration during the next 3-5 years is expected to be considerable, especially for consumer items such as cordless telephones, as well as wireless business systems. It therefore is important that this impending problem be acknowledged and taken into account in proceedings related to PR Docket 93-61.

Finally, it should be noted that as Teletrac modifies and refines its designs, the parameters used in the calculations presented here may change, but the fundamental conclusions will not. One such change might be a modified pulse shape to give a waveform that provides better ranging performance than the BPSK waveform that the current generation of Teletrac's equipment apparently uses.[15] The use of a more efficient ranging waveform would increase the constant k_β, allowing more accurate TOA estimation with a given RF bandwidth. This

15. Because of the parabolic weighting function in (2), signal spectra that concentrate most of the power at the outer edges of the band will have larger values of β and give better TOA estimates, given the bandwidth constraint (this is discussed in [5], pp. 405-407).

would actually *reduce* the amount of bandwidth needed for a given level of performance. Another potential change is an increase in the direct sequence chip rate, which would result in an increase in the RF bandwidth, given a fixed k_β. This would affect the C/I threshold, but not the E_b/N_0 threshold. One reason for this would be to reduce the message duration, thereby increasing capacity. However, as already discussed, once the bandwidth is sufficiently higher to provide the required TOA estimation accuracy at end-of-range, increasing bandwidth further to reduce message duration does not seem to be a spectrum-efficient tradeoff.

These conclusions imply that (1) the 902-928 MHz band, with its high potential for uncontrolled interference, may not be the appropriate band for wideband pulse-ranging systems such as Teletrac's, and (2) that 8 MHz per system may not be necessary in any event. These two points in turn suggest that another band should be sought for those systems, and the spectrum requirement may not be as great as has been assumed.

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[2] ____, Comments, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, filed with the FCC June 29, 1993.

[3] ____, Reply Comments, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, filed with the FCC July 29, 1993.

[4] Federal Communications Commission, Notice of Proposed Rule Making, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, adopted March 11, 1993; released April 9, 1993.

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[8] ____, Reply Comments, "In the Matter of Amendment of Part 90 of the Commission's Rules to Adopt Regulations for Automatic Vehicle Monitoring Systems," PR Docket No. 93-61, RM-8013, filed with the FCC July 29, 1993.

[9] Discussion with Yair Karmi (Vice President, Technology Development) and CZ Czerner (Vice President, Corporate Development) of PacTel Teletrac, during a meeting of the Telecommunications Industry Association Mobile & Personal Communications Consumer Radio Section, October 5, 1993, Washington, DC.

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[14] E. C. Jordan and K. G. Balmain, *Electromagnetic Waves and Radiating Systems*, Second ed., Englewood Cliffs, NJ: Prentice-Hall, 1968.

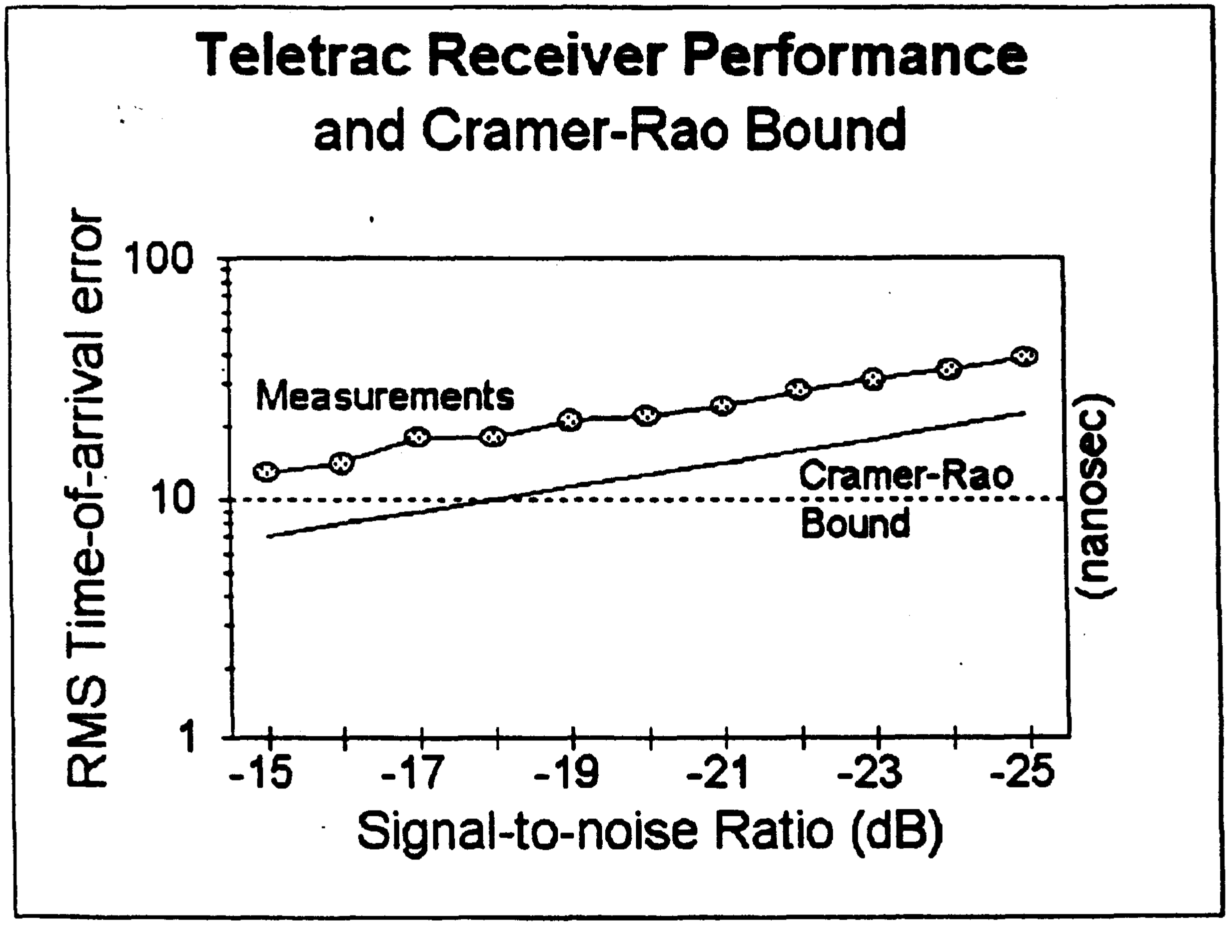


Figure 1

(reproduced from Appendix 2 of Teletrac's Comments, Fig. 12)

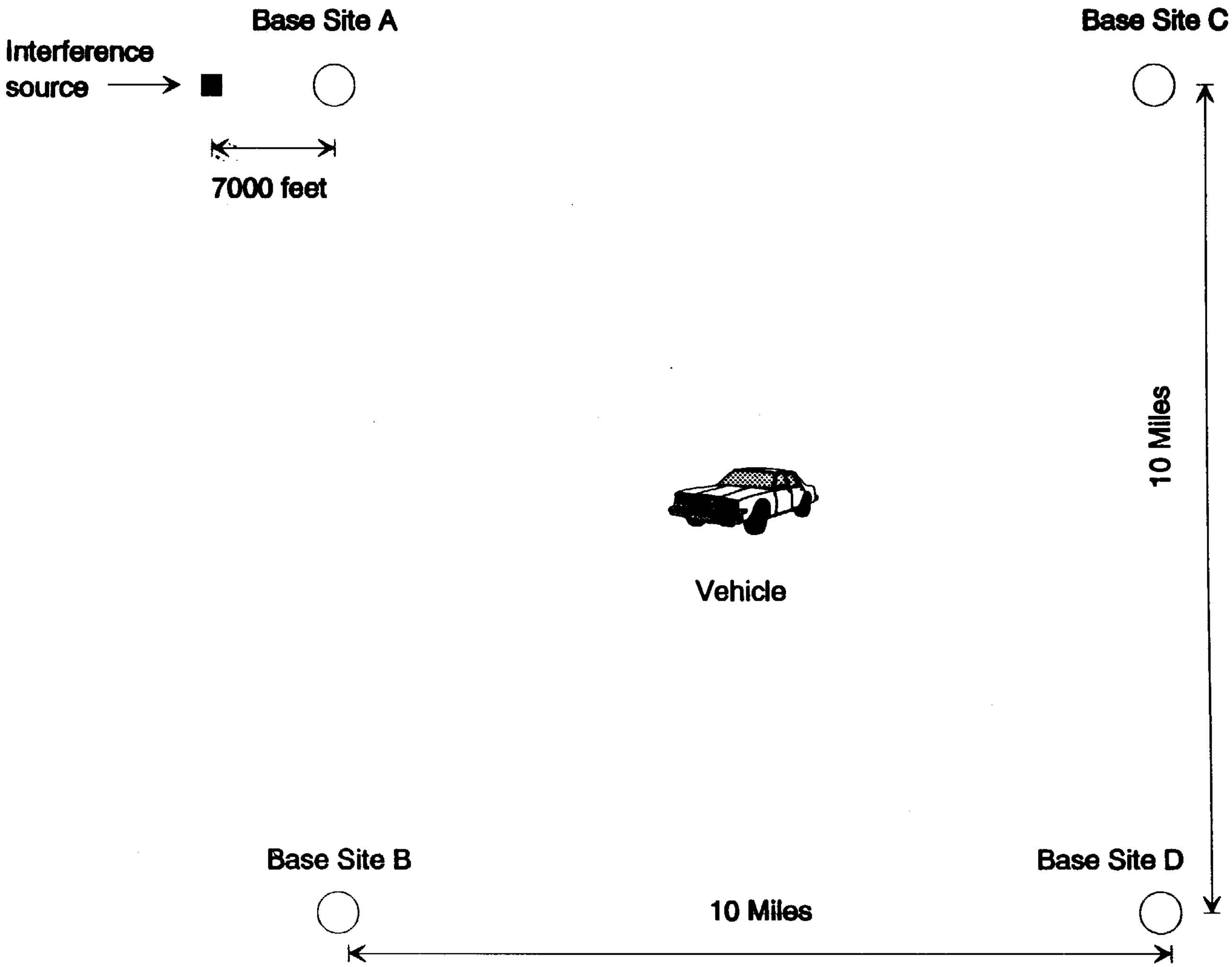
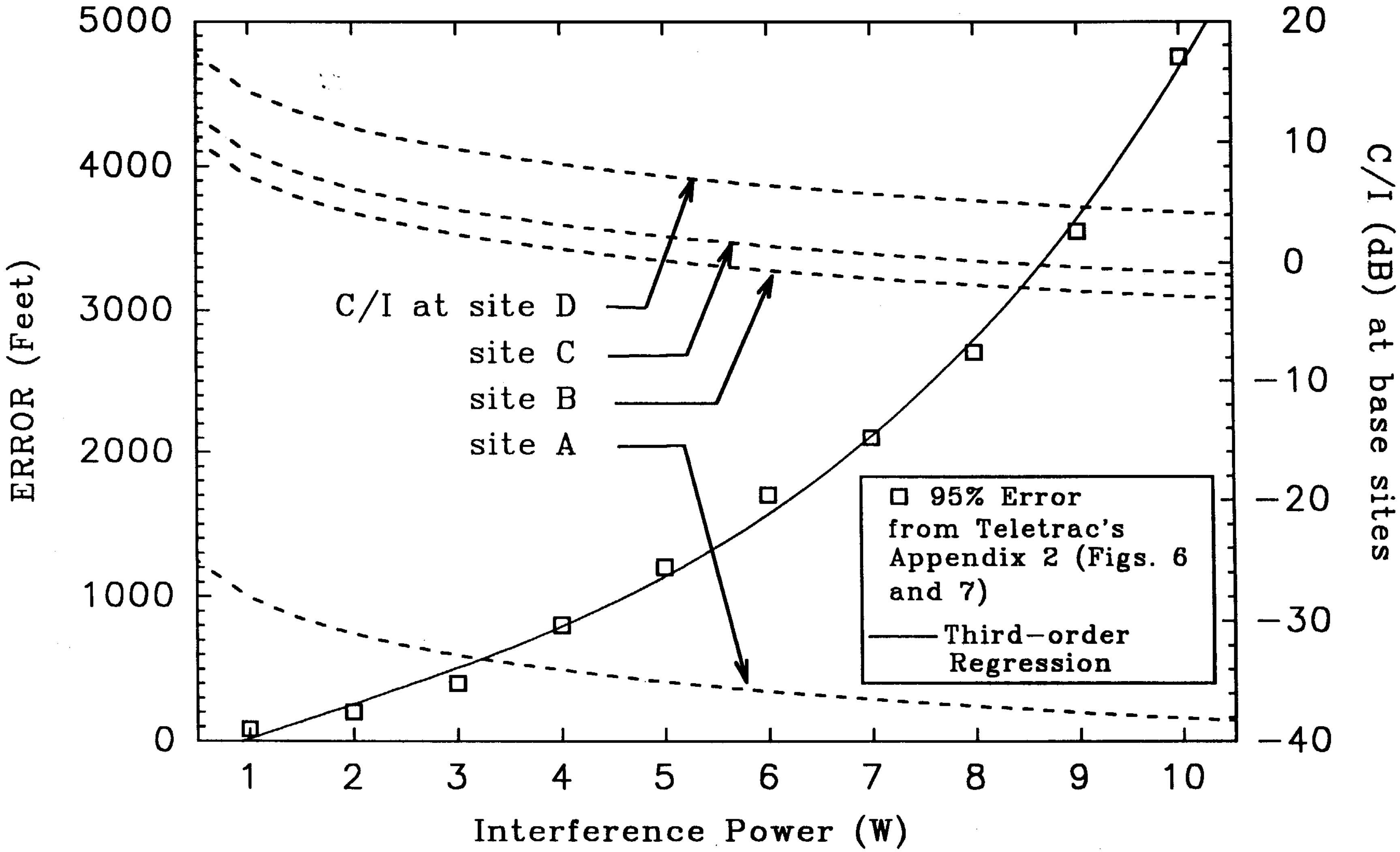


Figure 2 (Adapted from Appendix 2, Figure 4 of Teletrac's Petition)



ERROR (Feet)
5000
4000
3000
2000
1000
0
C/I (dB) at base sites
20
10
0
−10
−20
−30
−40
1
2
3
4
5
6
7
8
9
10
Interference Power (W)
C/I at site D
site C
site B
site A
95% Error from Teletrac's Appendix 2 (Figs. 6 and 7)
Third-order Regression

Figure 3

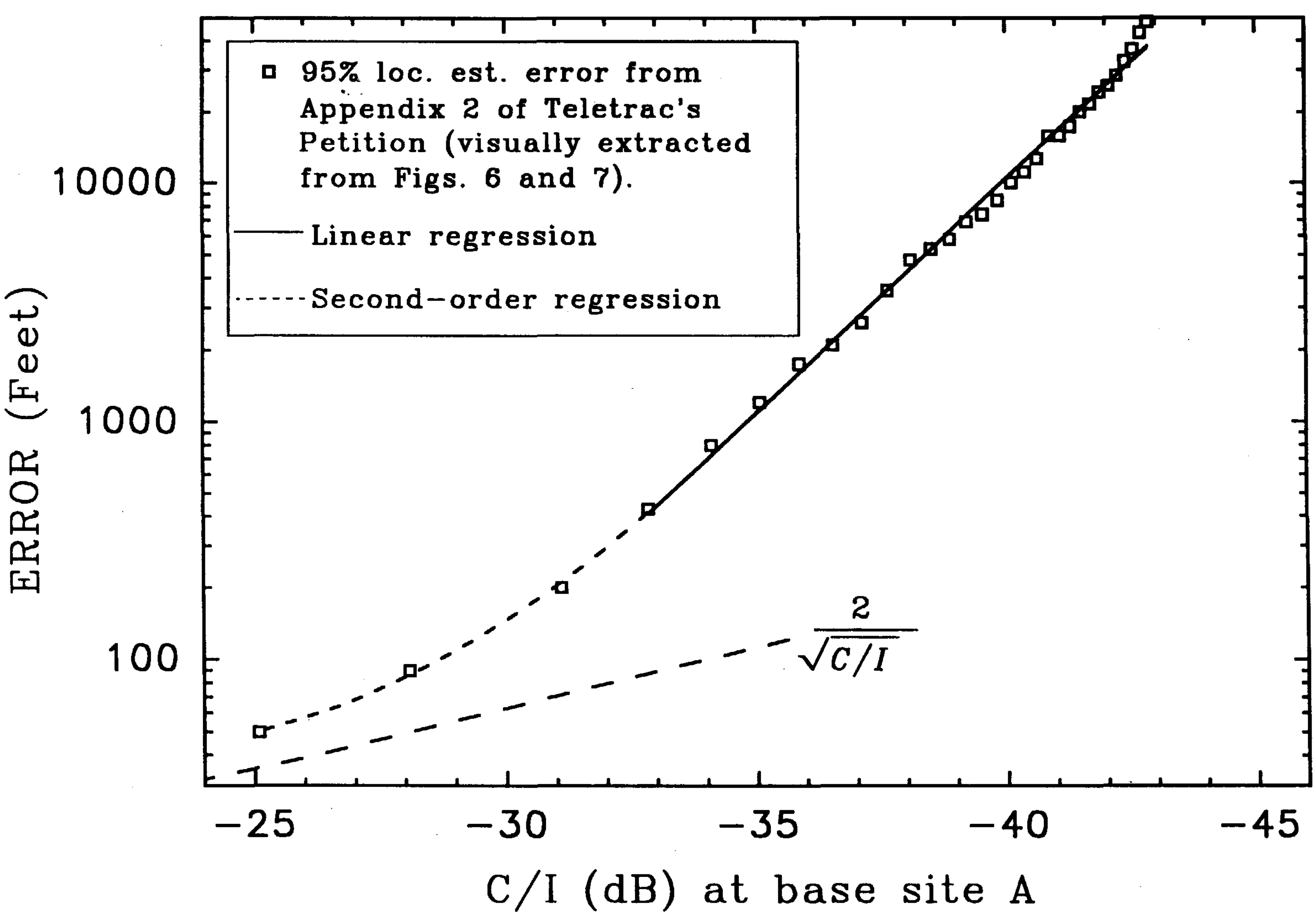
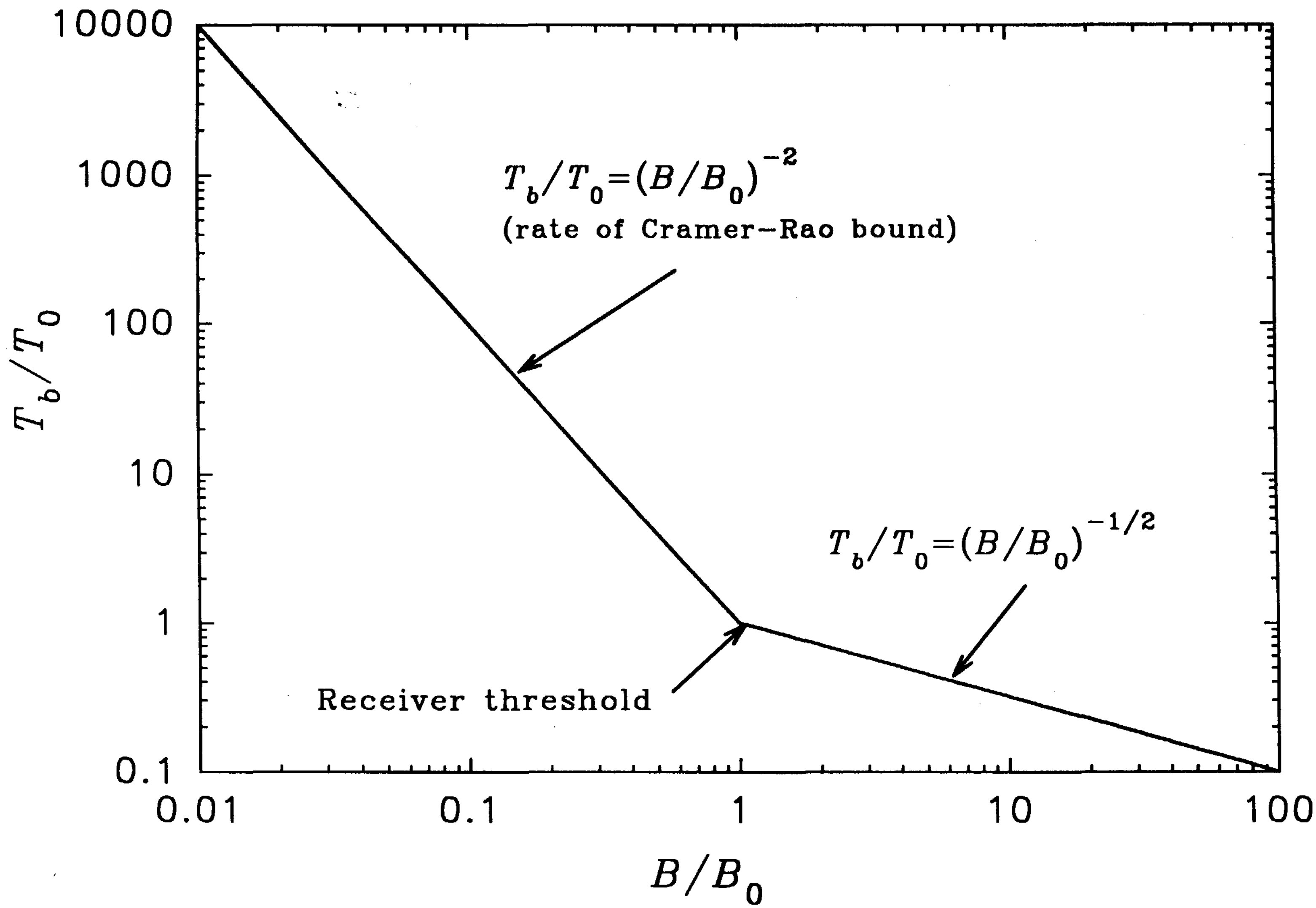
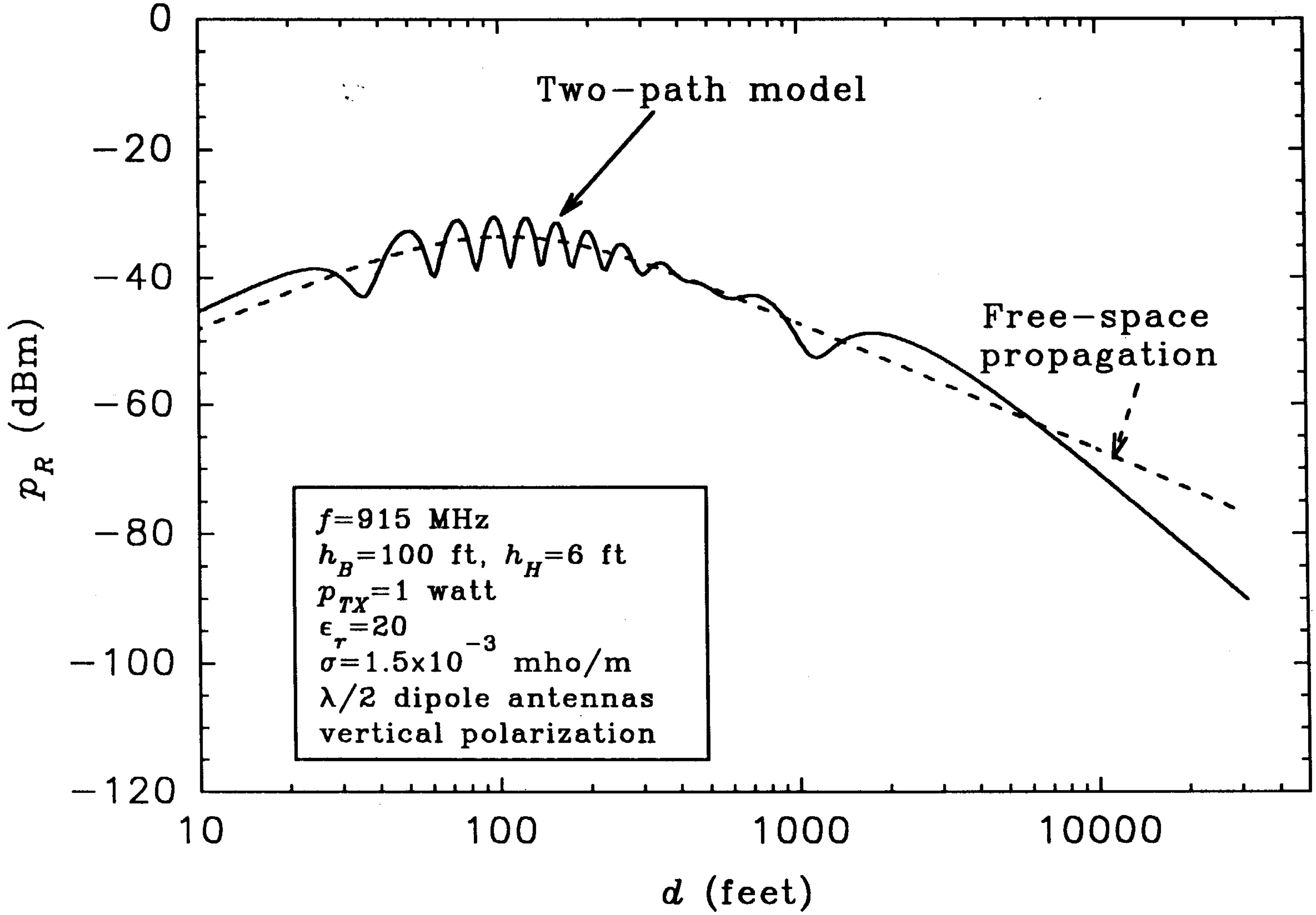

95% loc. est. error from Appendix 2 of Teletrac's Petition (visually extracted from Figs. 6 and 7).
Linear regression
Second-order regression
$\frac{2}{\sqrt{C/I}}$
ERROR (Feet)
10000
1000
100
−25
−30
−35
−40
−45
C/I (dB) at base site A

Figure 4



10000
1000
100
10
1
0.1
T_b/T_0
$T_b/T_0=(B/B_0)^{-2}$
(rate of Cramer-Rao bound)
$T_b/T_0=(B/B_0)^{-1/2}$
Receiver threshold
0.01
0.1
1
10
100
B/B_0

Figure 5



Two-path model
Free-space propagation
f=915 MHz
h_B=100 ft, h_H=6 ft
p_TX=1 watt
ε_r=20
σ=1.5x10^-3 mho/m
λ/2 dipole antennas
vertical polarization
p_R (dBm)
d (feet)
0
−20
−40
−60
−80
−100
−120
10
100
1000
10000

Figure 6

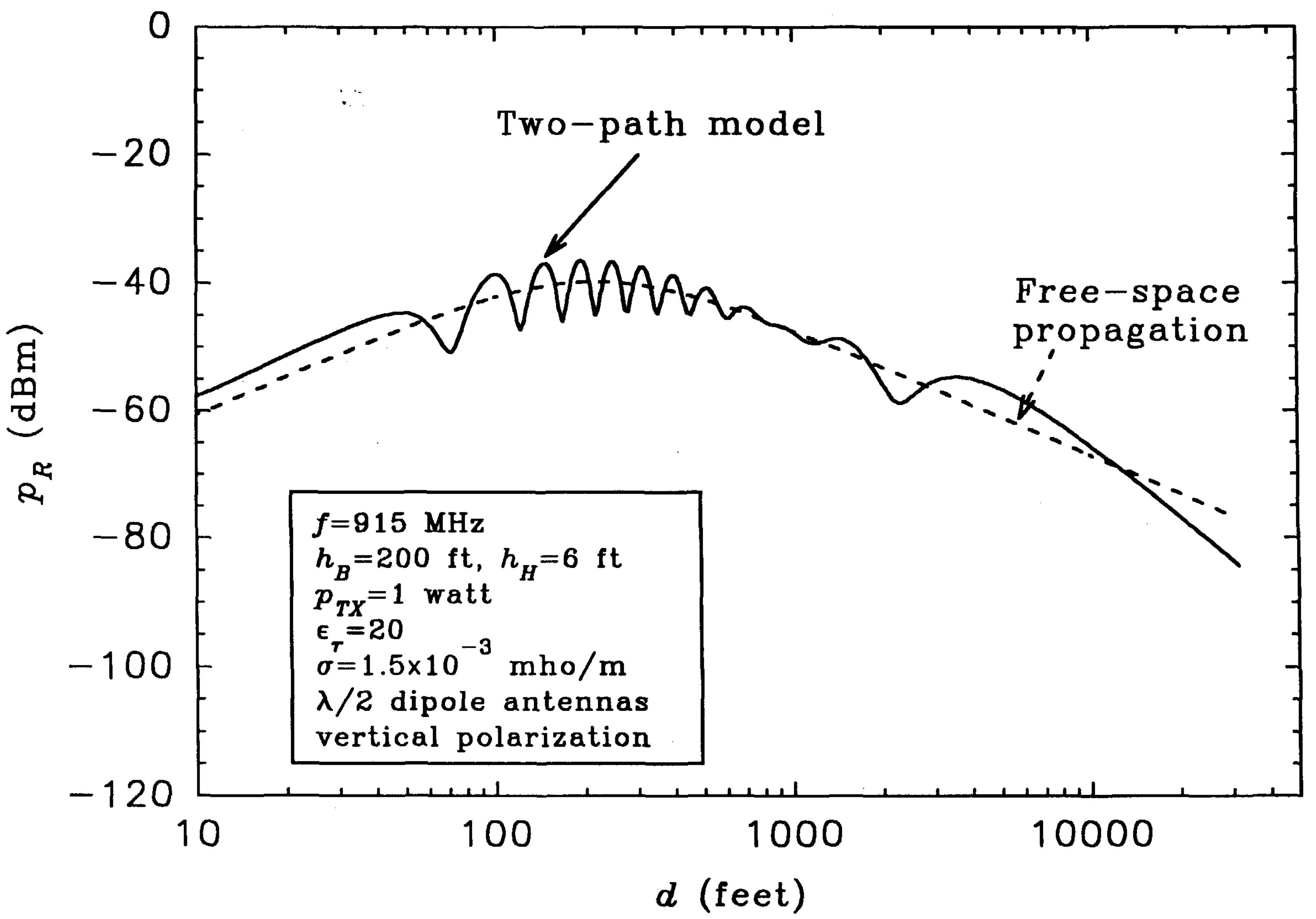
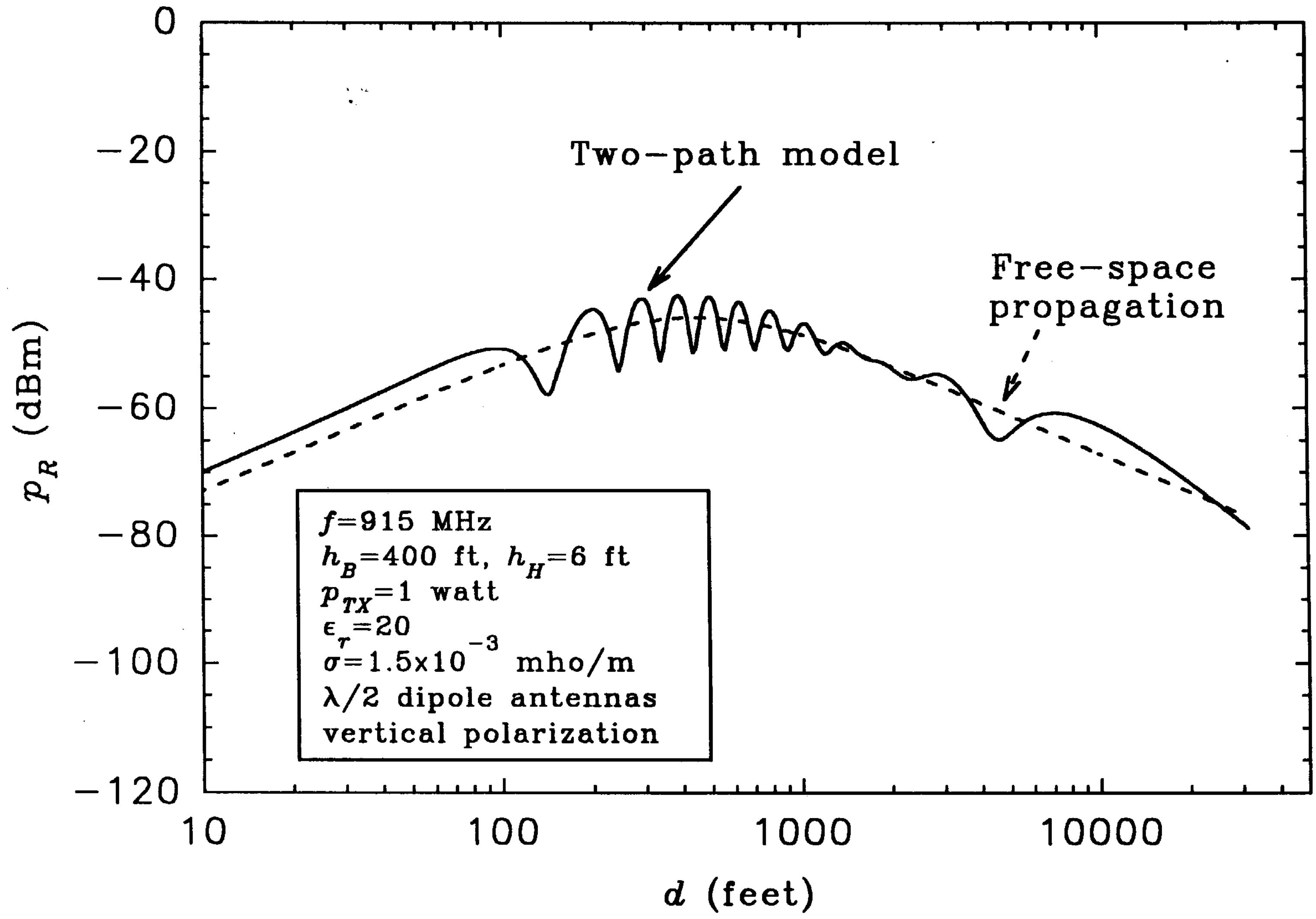
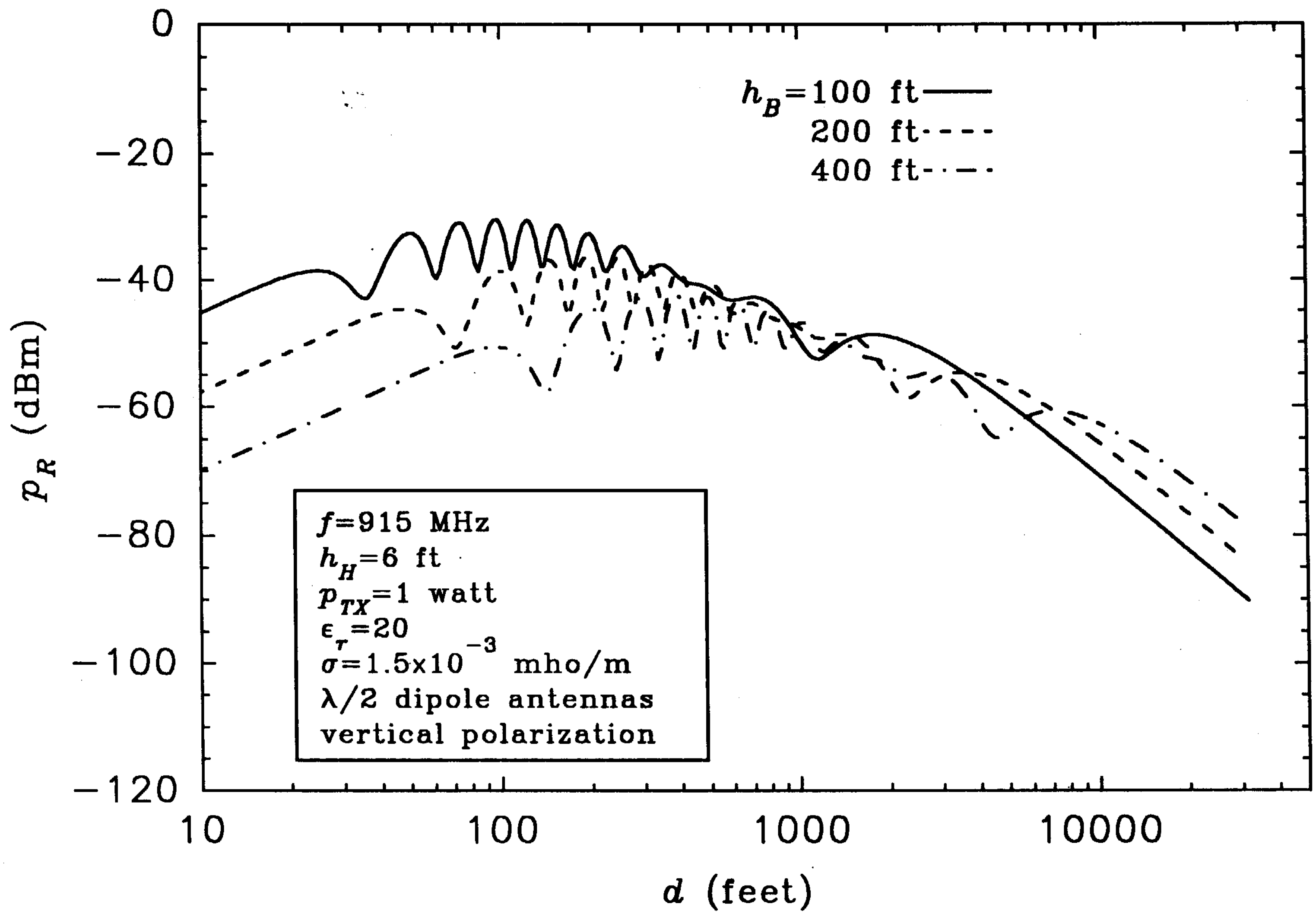

Two-path model
Free-space propagation
f=915 MHz
h_B=200 ft, h_H=6 ft
p_{TX}=1 watt
ϵ_r=20
$\sigma=1.5\times10^{-3}$ mho/m
$\lambda/2$ dipole antennas
vertical polarization
p_R (dBm)
d (feet)
0
−20
−40
−60
−80
−100
−120
10
100
1000
10000

Figure 7



0
−20
−40
−60
−80
−100
−120
10
100
1000
10000
d (feet)
p_R (dBm)
Two−path model
Free−space propagation
f=915 MHz
h_B=400 ft, h_H=6 ft
p_{TX}=1 watt
ϵ_r=20
σ=1.5x10^{-3} mho/m
λ/2 dipole antennas
vertical polarization

Figure 8



0
−20
−40
−60
−80
−100
−120
10
100
1000
10000
p_R (dBm)
d (feet)
h_B=100 ft
200 ft
400 ft
f=915 MHz
h_H=6 ft
p_{TX}=1 watt
ϵ_r=20
σ=1.5x10^{-3} mho/m
λ/2 dipole antennas
vertical polarization

Figure 9